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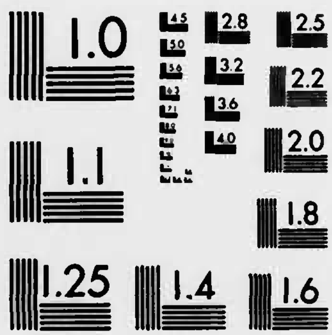

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Department of
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EXPERIMENTAL RESEARCH ON RAIL VEHICLE SAFETY USING DYNAMICALLY SCALED MODELS

by

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OBJECTIVE

The objectives of this research are to develop experimental techniques for the study of rail vehicle dynamic through the use of scaled models on tangent track, and to develop a structured experimental data base on the characteristics of rail car trucks. The complex interactions between track, wheels, suspensions, and vehicles are the causes of derailments, rapid deterioration of vehicle and track components, poor passenger and freight ride quality, and low operating speeds. These problems are significant because of the massive capital expenditures presently required for equipment rehabilitation to restore efficient and reliable operation. The establishment of a larger and more systematically structured experimental data base than that feasible from full-scale testing will enable the validation of analytical tools useful in design and evaluation of alternative technologies and safety criteria.

The experimental program consists of static and dynamic measurements of rail vehicle trucks at scaled speeds of up to 200 mph. Dynamic similitude in the one-fifth scale model (approximately twelve-inch gauge) is achieved by substituting a material with low elastic modulus for steel at the wheel/rail contact surfaces. Complex nonlinear dynamic phenomena, such as truck hunting, limit cycle oscillations, and incipient derailment, will be examined in controlled tests, and compared with results from theoretically derived simulation models and evidence from experiments on full-scale vehicles.

SUMMARY

The scope of work during the first year of the program (June 29, 1976 - June 28, 1977) includes: (1) the design and fabrication of a scale model track, single wheelset, test carriage, and associated instrumentation; (2) measurement of wheelset displacement-force characteristics at steady velocity; (3) measurements of wheel-climb phenomenon; and (4) comparison of measured results with theoretical predictions. The results of this work will be applied to the design of a complete scale model truck and measurement of its static and dynamic stability characteristics.

Results to Date

Analysis and Experimental Design:

The analytical and experimental design phases of the program are completed. The design of the experiment consists of the following elements:

a) Design study of similitude parameters to determine model scale to be used over the course of the program; The selected track gauge is 12 inches, or a geometric scale factor of $\lambda = 0.2$.

b) Design of the track support structure and rail system; Static and dynamic deflections were analyzed in detail; the stiffness, cost of fabrication, and availability of standard section shapes were included in a tradeoff analysis.

c) Analysis of random irregularities in track alignment, elevation, and gauge, to determine necessary construction tolerances. Results showed that damping ratios down to 0.01 may be measured from transient response testing without the signal being masked by the force response due to the random track profile.

d) Detailed design of wheelset, idler carriage, linkage, and instrumentation systems. The linkage system, shown schematically in Figure 10, was designed to permit all necessary wheelset degrees-of-freedom. The principal force measuring device, a six-component strain-gage balance, is maintained in an attitude parallel to the track so that forces and moments are measured in the rail coordinate system.

e) Computer simulation of experiment to determine full range of measured variables. Nonlinear effects simulated as functions of time include the following:

New wheel and rail profiles

Contact ellipse shape and size

Asymmetric loading of wheelset

Contact angles and effective conicity

Traction-limited creep force relation

Effects of rotating co-ordinate system

Fabrication of Apparatus:

a) The 800-foot track structure has been completed, with piers secured to the concrete slab floor. The pier heights have been coarse adjusted to provide an approximately level surface for subsequent construction. The LEXAN track rails have been machined to the standard new rail profile.

b) A small roller rig used for calibration experiments of tangential, lateral, and spin creep was completed.

Experimental Results:

a) Experimental measurements of lateral and tangential creep forces using LEXAN wheels on the roller rig showed that the contact forces are exactly reproduced in scale. Agreement with theory was demonstrated using scaled values for shear modulus.

Work to be Completed in First Year

Fabrication of Apparatus:

a) Installation and alignment of rails on track structure (2/15/77).

b) Completion of wheelset/carriage/linkage system and associated instrumentation (3/1/77).

Experimental Results:

a) Measurement of steady-state wheelset force/displacement relations for ranges of external forces and velocities, for the wheelset at fixed yaw angle. The full nonlinear region will be explored. The results will be compared to the simulation results described above. The validated results will be used to simplify the wheelset model for use in complete truck models (4/15/77).

b) Measurement of incidence of wheel-climb for the fixed yaw angle wheelset. Comparison with published results (4/15/77).

c) Measurement of hunting, critical speed, and dynamic wheelclimb for a single wheelset. Comparisons with linear and nonlinear (quasi-linear) theory (5/1/77).

ALIGNMENT SPECIFICATIONS FOR PRINCETON MODEL TRACK

Introduction

Measurements of the dynamic characteristics of railcar trucks can, in general, be made by recording either the transient responses to programmed discrete events, such as applied forces or rail displacements, or spectral responses to random inputs, such as rail irregularities. The latter possibility is inappropriate for use in the Princeton experiments for two reasons:

a) Analysis of random processes with high bandwidths requires long data records to yield statistically meaningful results. Simulation of spectra typical to ground vehicle dynamics require from 10,000 to 20,000 data points [1, 2]. On the Princeton track the maximum data rate per channel would be equivalent to a data point every 0.44 millisecond. Data transmission, storage, and processing requirements are formidible, and are infeasible without a dedicated minicomputer.

b) Most methods available for processing random data apply only to linear systems. The Princeton experiments by design include investigations of nonlinear behavior. Statistical linearization techniques have been applied to the truck dynamic problem [5]; these methods are more useful in design than for model verification due to the amount of dynamic information lost during the averaging process.

From the above, transient response testing is selected for our test program. It follows that the responses due to random inputs be minimized to maximize "signal to noise" ratios, requiring an analysis of random inputs as part of the track design process.

Track Model

The spectral densities of the track alignment, elevation, cross-elevation, and gauge can be used to characterize the track irregularity. At this point we anticipate that cross-elevation and gauge will be accurately set and maintained, so that our major concerns are track vertical and lateral irregularities. Vertical displacement spectra have been shown to be appropriate track roughness measures, but some question exists regarding the use of lateral spectra, due to the nonlinearities in wheel/rail contact force relations and the effects of wheel/rail profiles and surface condition [7]. Since profiles and surface contamination at the Princeton track will be controlled, lateral spectra may be appropriate.

The track roughness model in [1] is used in our design. For irregularities illustrated in Figure 1, the spectrum is given by,

$$S(\Omega) = \frac{4\sigma_c^2}{h^3\Omega^4}(1 - \cos(h\Omega)) + \frac{4\sigma_b^2}{h_b^3\Omega^4}(3 - 4\cos(h_b\Omega) + \cos(2h_b\Omega)) \tag{1}$$

where Ω = spatial frequency in rad/ft

σ_c = standard deviation of terrain elevation error

σ_b = standard deviation of construction error

h = distance between terrain elevation points

h_b = distance between construction survey points

Equation (1) assumes random errors in construction at discrete track locations, with straight line segments connecting the points. Since the Princeton track is composed of multiple span beams pinned at these points, it follows that our track will have less high frequency content than the above model, with slightly more signal at twice the pin spacing. The pinned, misaligned track was examined in [8], but only for single spans. For small errors, Equation (1) may not be very different from the multiple-span case.

A surface roughness model is given in [1] to be added to (1). Since the rails are being machined to <0.001" smoothness, this irregularity is assumed to be insignificant.

Track Parameters

The track vertical supports, each adjustable, are spaced four feet apart, specifying h_b . The lateral alignment points may be designed to be from two to four feet apart. A survey of the existing concrete slab floor showed that a terrain error of σ_c = 0.025" at 200-foot spacings would allow us to use pier heights of one to three inches. Pier heights should be small to minimize lateral track deflections. The remaining design parameters are vertical σ_b and lateral σ_b , σ_c , and h_b (assuming lateral h is the same as for vertical, for convenience).

Track Irregularity Criteria

Two criteria have been applied to determine the track alignment specifications. The first test is that the Princeton track, in scale, should be a factor of ten straighter than the best existing in-service track. Spectral densities for Class 6 track are shown in Figures 2 and 3 (from [3]).

In Figures 4 and 5, predicted spectral densities for the Princeton track are plotted with the above scaled specification. Even with relatively coarse tolerances the vertical density is acceptable. Somewhat closer tolerances are required to meet the lateral specification in the 0.1 to 0.5 cycles/ft range, where kinematic hunting is expected.

A second criterion examined is RMS truck lateral displacement. The linearized truck model used in [4] yielded frequency responses in Figure 6 that could be approximated as second-order, with a natural frequency about equal to the kinematic hunting frequency and damping ratios from zero to 0.35 for operation below critical velocity.

Using the approximate second-order transfer function the relative truck/rail lateral displacement spectrum was computed, as shown in Figures 7 and 8 for trucks with a scaled kinematic wavelength, λ_K , of five feet. These plots show clearly that only irregularities in the range of three to ten feet are important.

The dependence of RMS lateral displacement on damping ratio (and hence truck velocity) is similar to that calculated in [4] using a more complete dynamic model. Although the noise level due to random inputs increased as damping is reduced, the truck damping due to transient inputs can still be measured down to very low values ($\simeq 0.01$). From the tradeoff

curves in Figure 9 the adjustment spacing length h_b is selected to be three feet, with a target σ_b of 0.005" to 0.010".

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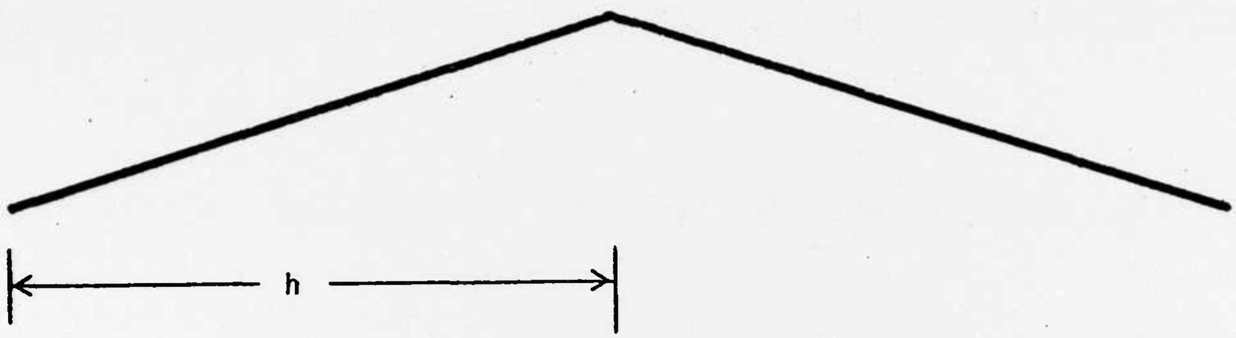
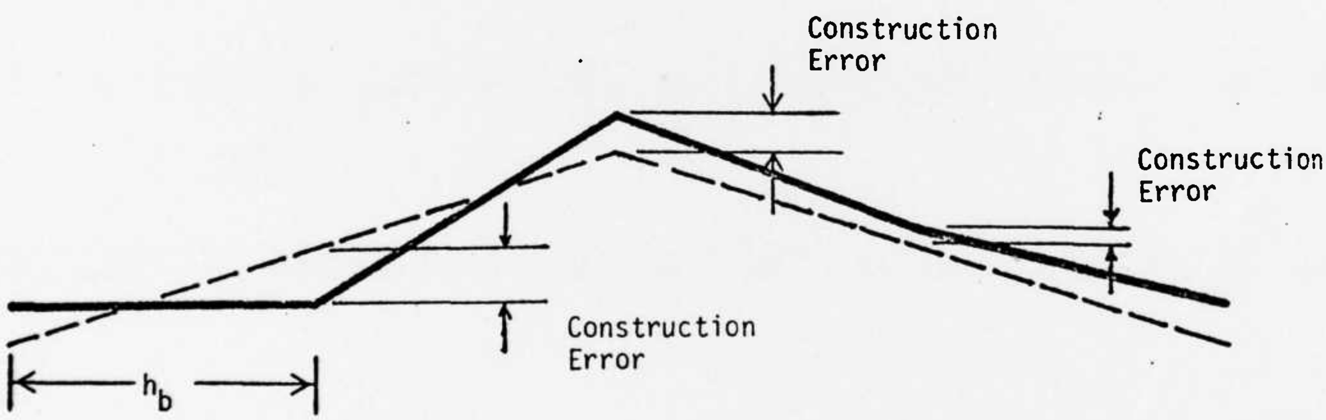


Figure 1 Guideway profile with terrain irregularities only. [1]



Guideway profile with surveying and construction errors superimposed on a profile with terrain irregularities.

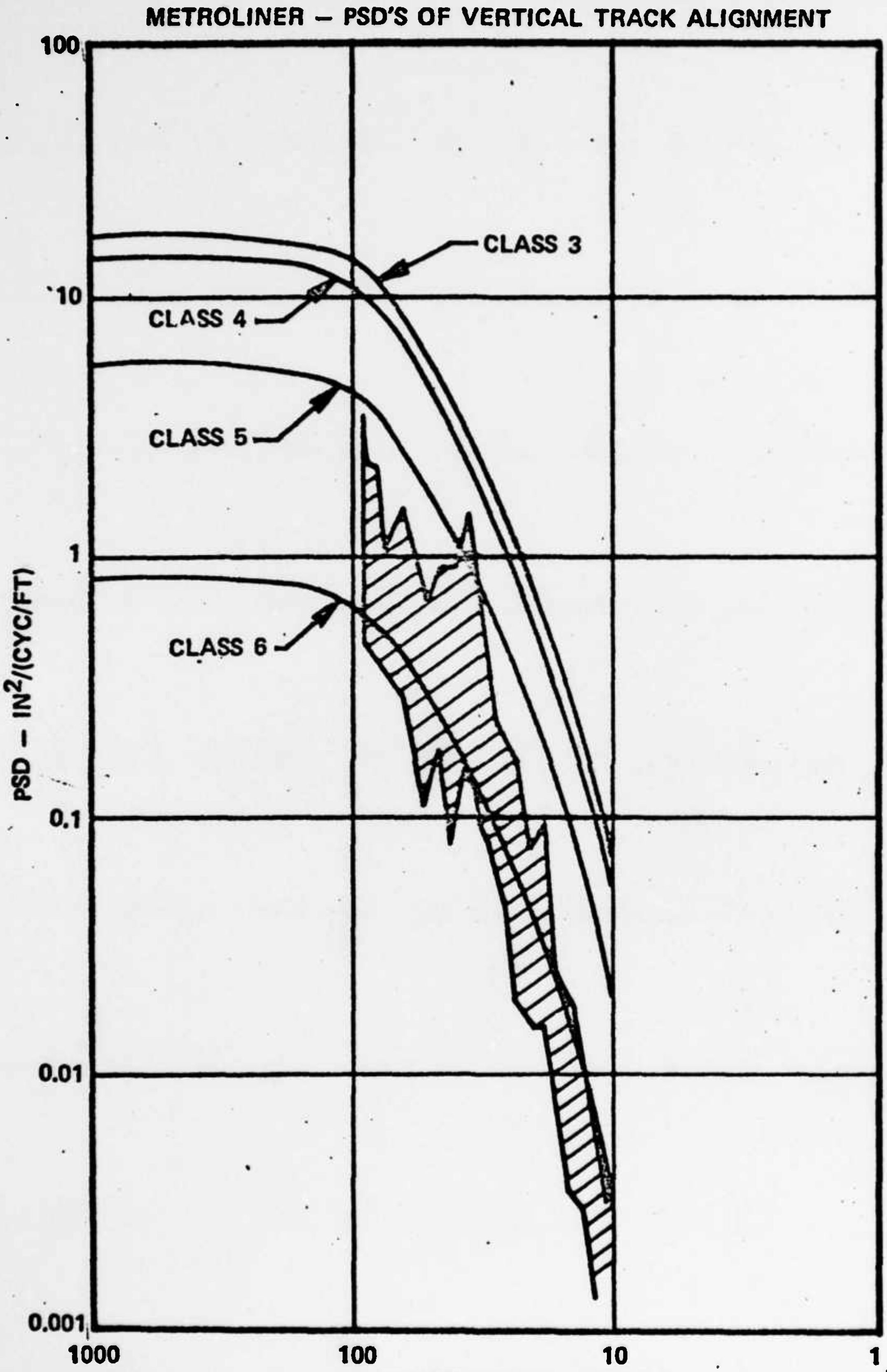


Figure 2 Power Spectral Densities of Metroliner Track Roughness – Measured Envelope and Analytical Approximations of Vertical Alignment [3]

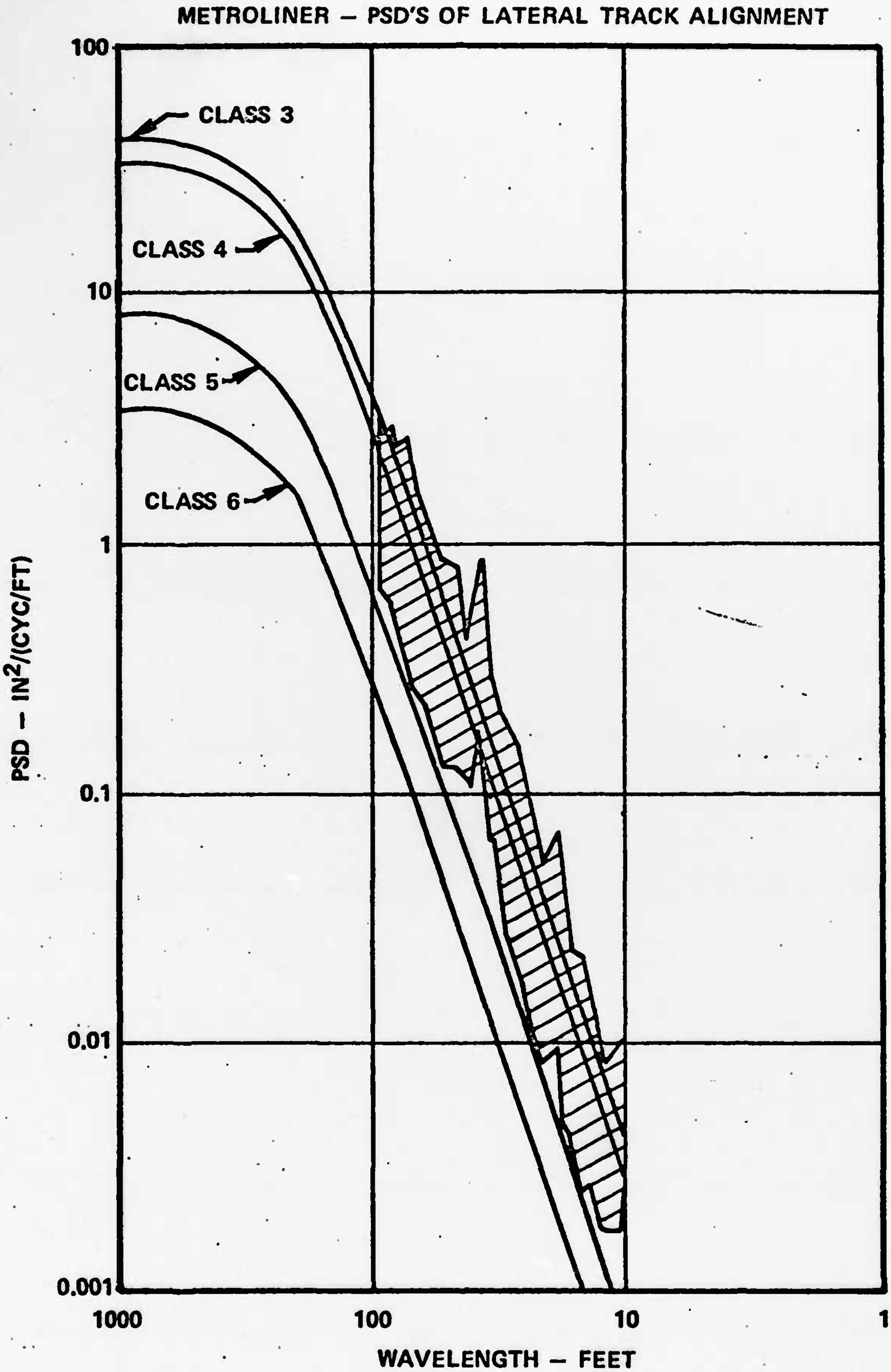


Figure 3 Power Spectral Densities of Metroliner Track Roughness – Measured Envelope and Analytical Approximations of Lateral Alignment [3]

1) SIGMAB (IN.)= 0.025
2) HB (FT.) = 4
3) H (FT.) = 200
4) SIGMAC (IN.)= 0.25

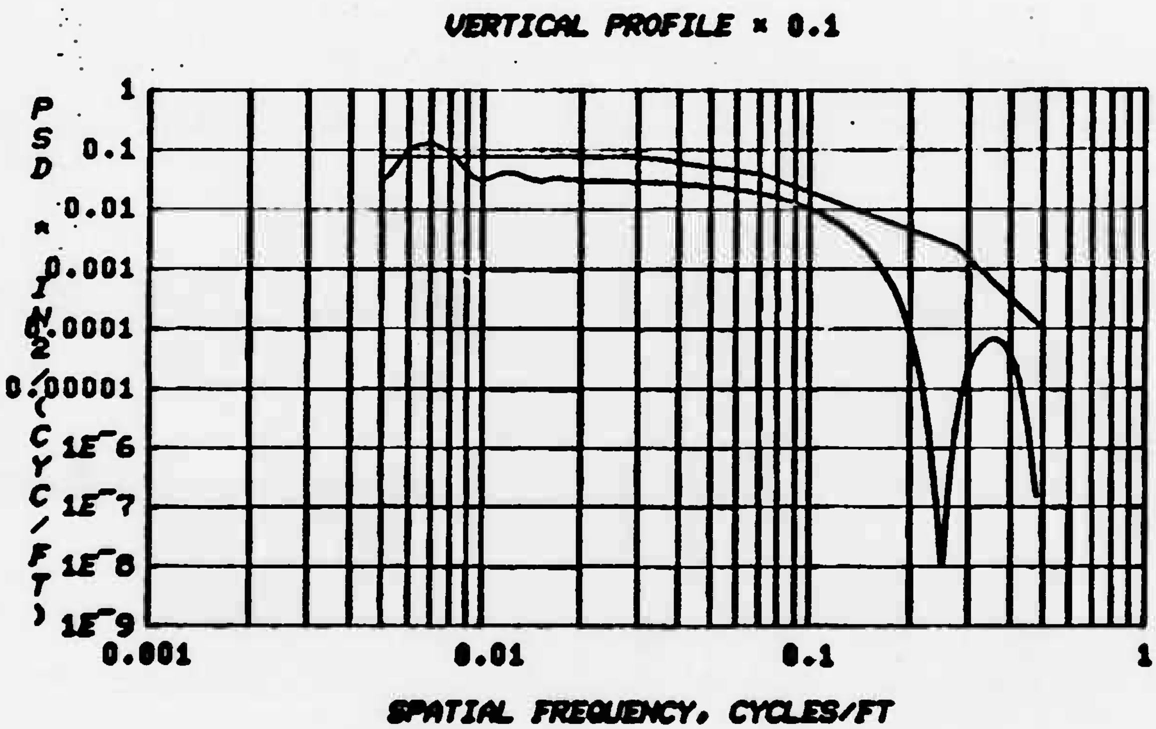


Figure 4

1) SIGMAB (IN.)= 0.01
2) HB (FT.) = 3
3) H (FT.) = 200
4) SIGMAC (IN.)= 0.1

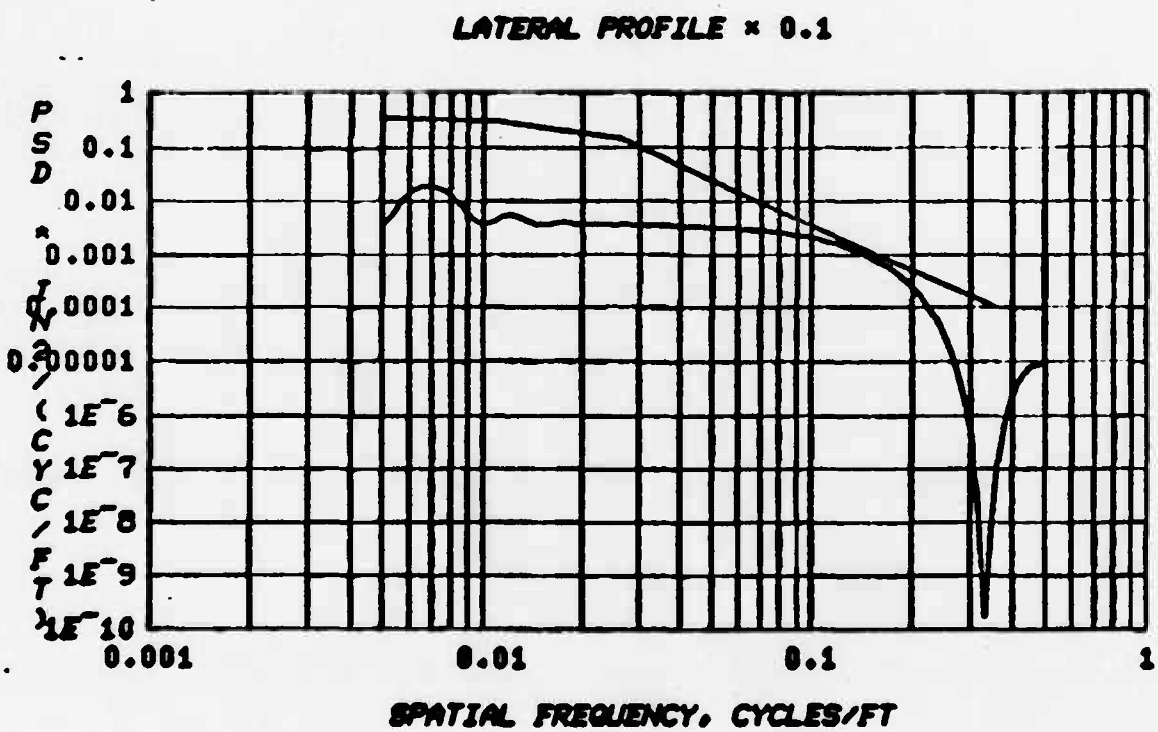


Figure 5

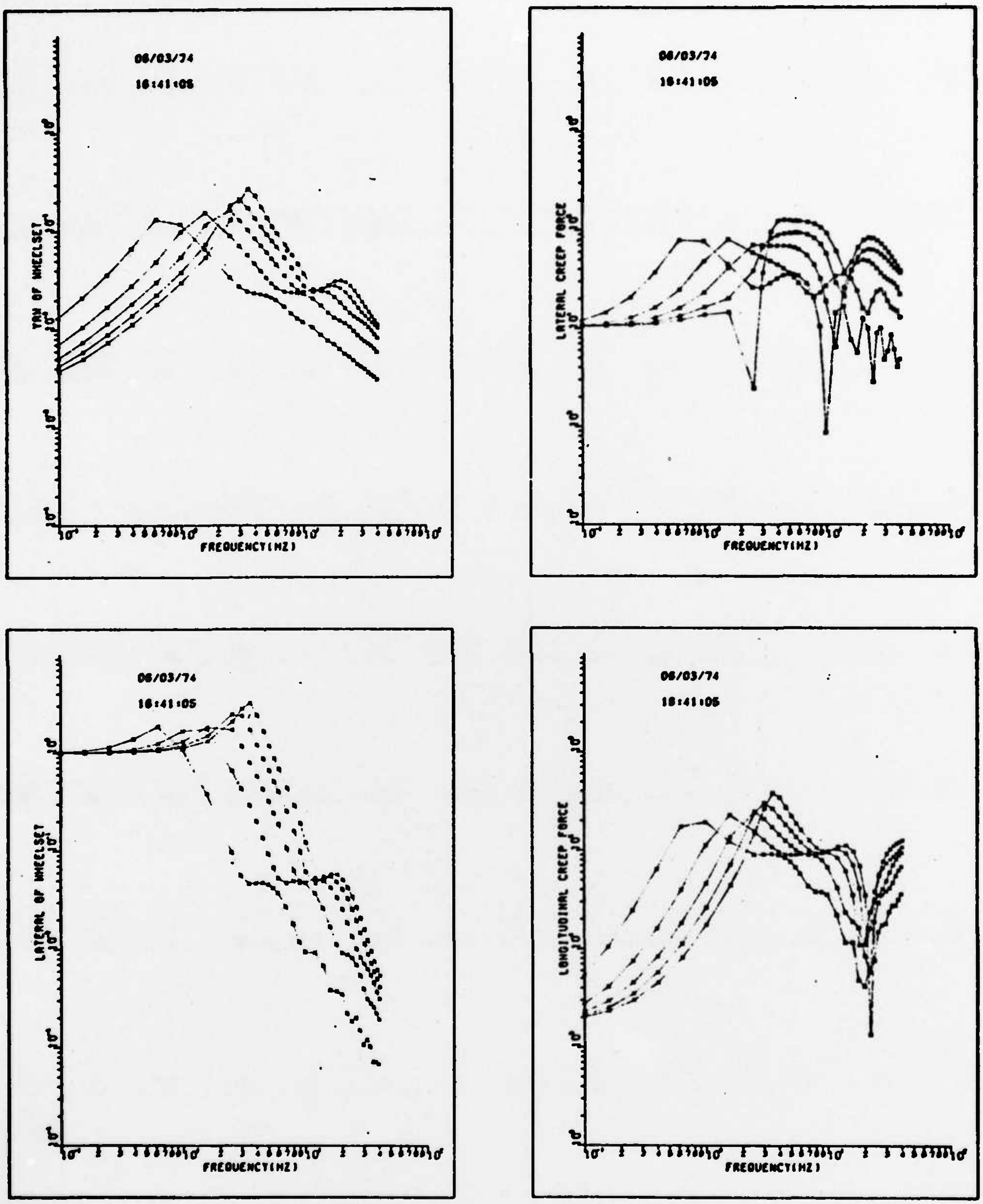
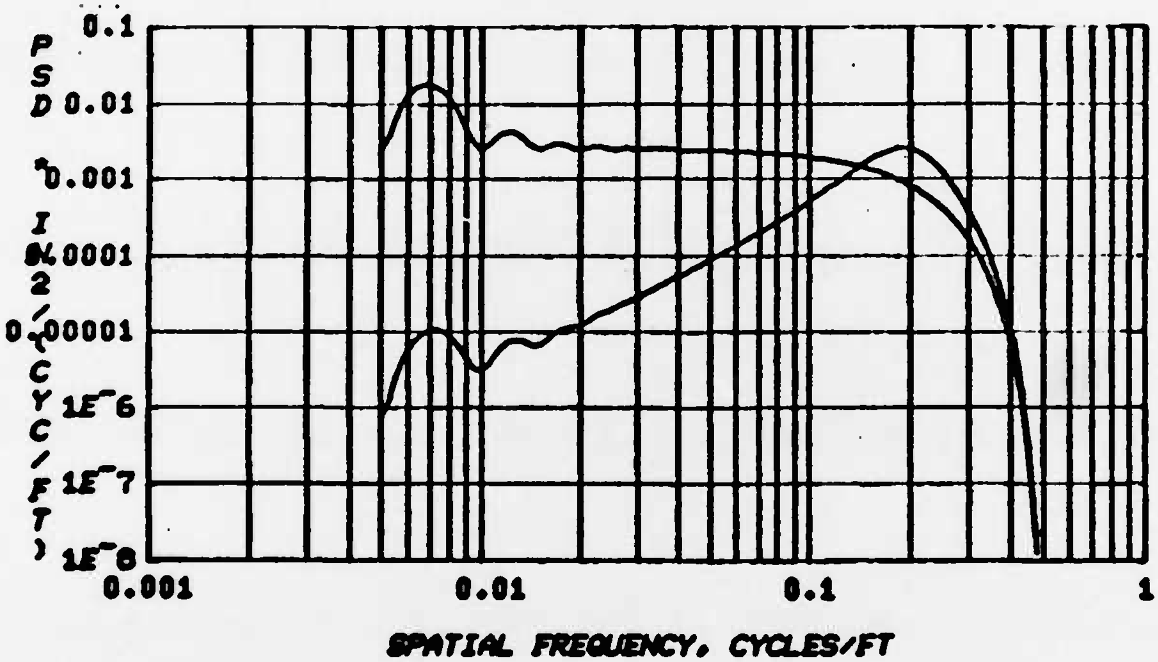


Figure 6 - Frequency responses at various velocities[4].

LAMBDAK, FT. = 5
ZETA = 0.35
RMS ERROR, IN. = 0.01809628797

Figure 7

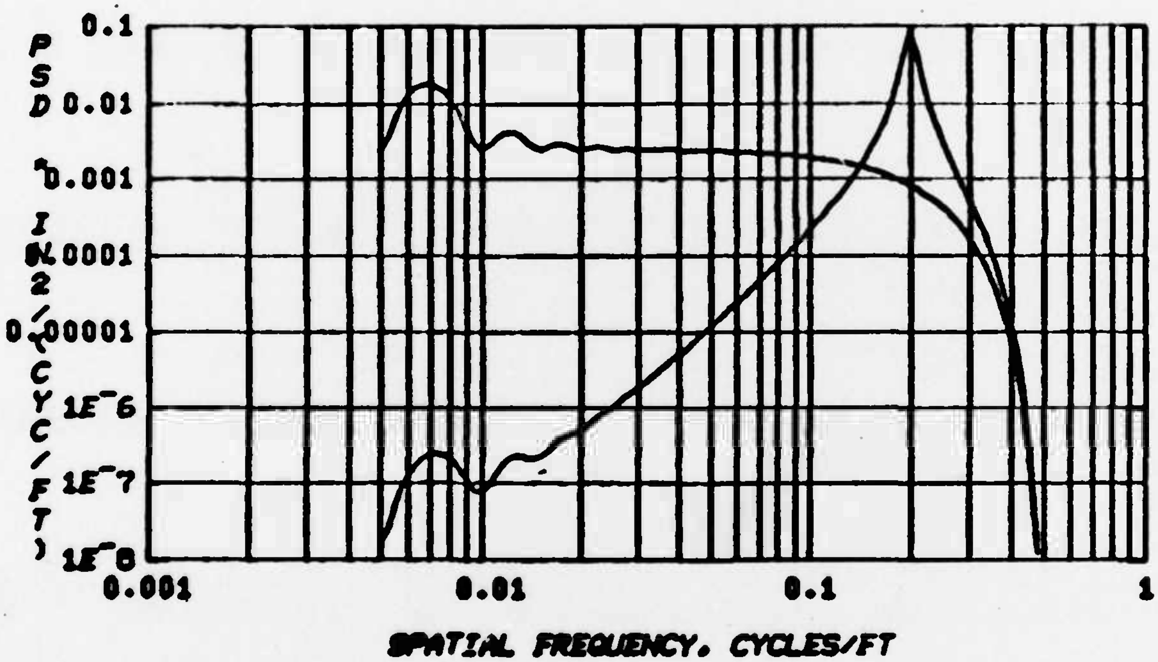
LATERAL RESPONSE

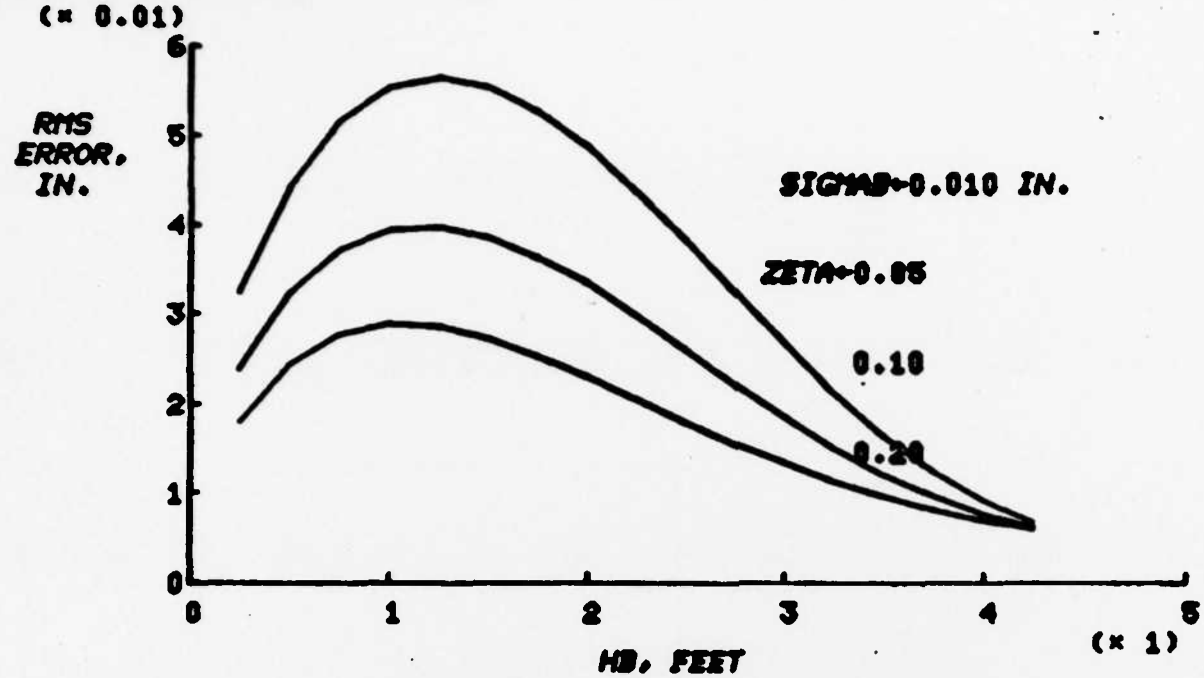


LAMBDAK, FT. = 5
ZETA = 0.05
RMS ERROR, IN. = 0.04878228442

Figure 8

LATERAL RESPONSE





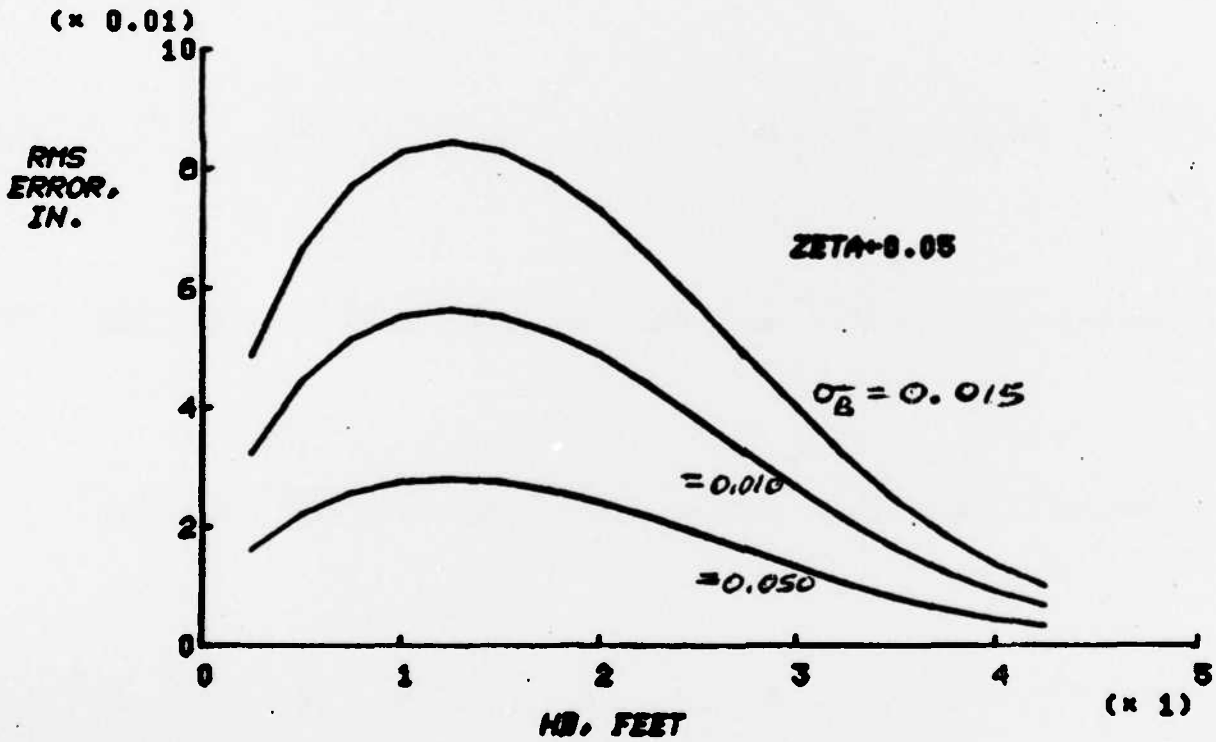


Figure 9. Effect of alignment error σ_b , alignment spacing h_b, and truck damping ratio on RMS lateral error.

MECHANICAL DESIGN OF CARRIAGE LINKAGE SYSTEM

Introduction

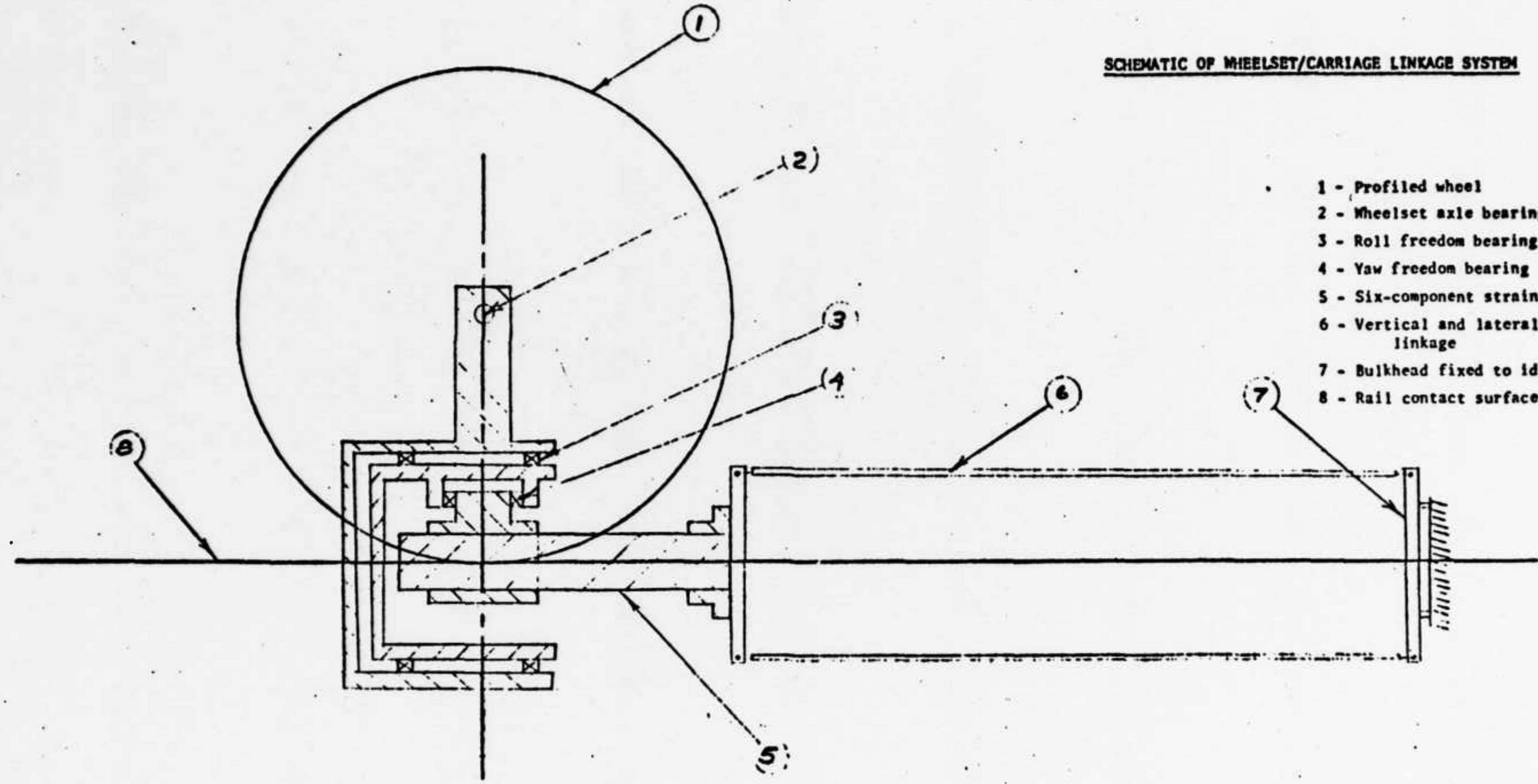
A critical component in the Princeton scale model experiments is a linkage system through which all forces and displacements are measured or applied. The linkage system (see Figure 10) described below can be used for several types of experiments for a single wheelset. By replacing the wheelset with the truck center bolster, the linkage can then be used without modification for full truck experiments.

Application of Coordinate Systems

As described in Quarterly Report I, the coordinate systems are important to the dynamics of the wheelset: rail, wheelset, and contact plane axes. The linkage is designed so that all forces and moments on the wheelset or truck are applied and measured in rail coordinates. The wheelset or truck is allowed all important degrees of freedom: lateral and vertical displacement, yaw, roll, wheelset axle rotation, and truck frame pitch. Longitudinal displacement is constrained to be that of the carriage. Note that all above freedoms are essential if wheel contact is to be maintained simultaneously in all wheelset positions. Failure to recognize the importance of geometric constraints has been a source of difficulty in previous experimental investigations.

The force measuring system is centered between the two contact points, minimizing roll moments due to horizontal components of the lateral creep forces. The center of rotation of all wheelset angular displacements except roll is located at the center of the wheelset body.

SCHEMATIC OF WHEELSET/CARRIAGE LINKAGE SYSTEM



1 - Profiled wheel
2 - Wheelset axle bearing
3 - Roll freedom bearing
4 - Yaw freedom bearing
5 - Six-component strain gage balance
6 - Vertical and lateral parallelogram linkage
7 - Bulkhead fixed to idler carriage referen
8 - Rail contact surface

Figure 10

Description of Linkage

All mechanical freedoms in the linkage are rotational bearings or flexual pivots; these components were chosen over translational bearings to minimize alignment problems. Forces and moments are measured with a six-component strain gage balance whose axis is always parallel to the track, fixed by lateral and vertical parallelogram linkages anchored to a bulkhead on the idler carriage rolling on the track. The linkages are provided to give vertical and lateral freedom to the wheelset or truck.

The remaining rotational freedoms are provided by bearings as shown. Stiffness and damping coefficients in each degree of freedom can be isolated by similar linkage locking. In full dynamic experiments all constraints are free. In our initial experiments, the yaw angle will be fixed by locking the yaw bearing.

External forces are applied to the parallelogram linkage in rail coordinates. Suspension forces are applied by fixing the ends of the suspension elements to the carriage and wheelset (or truck).

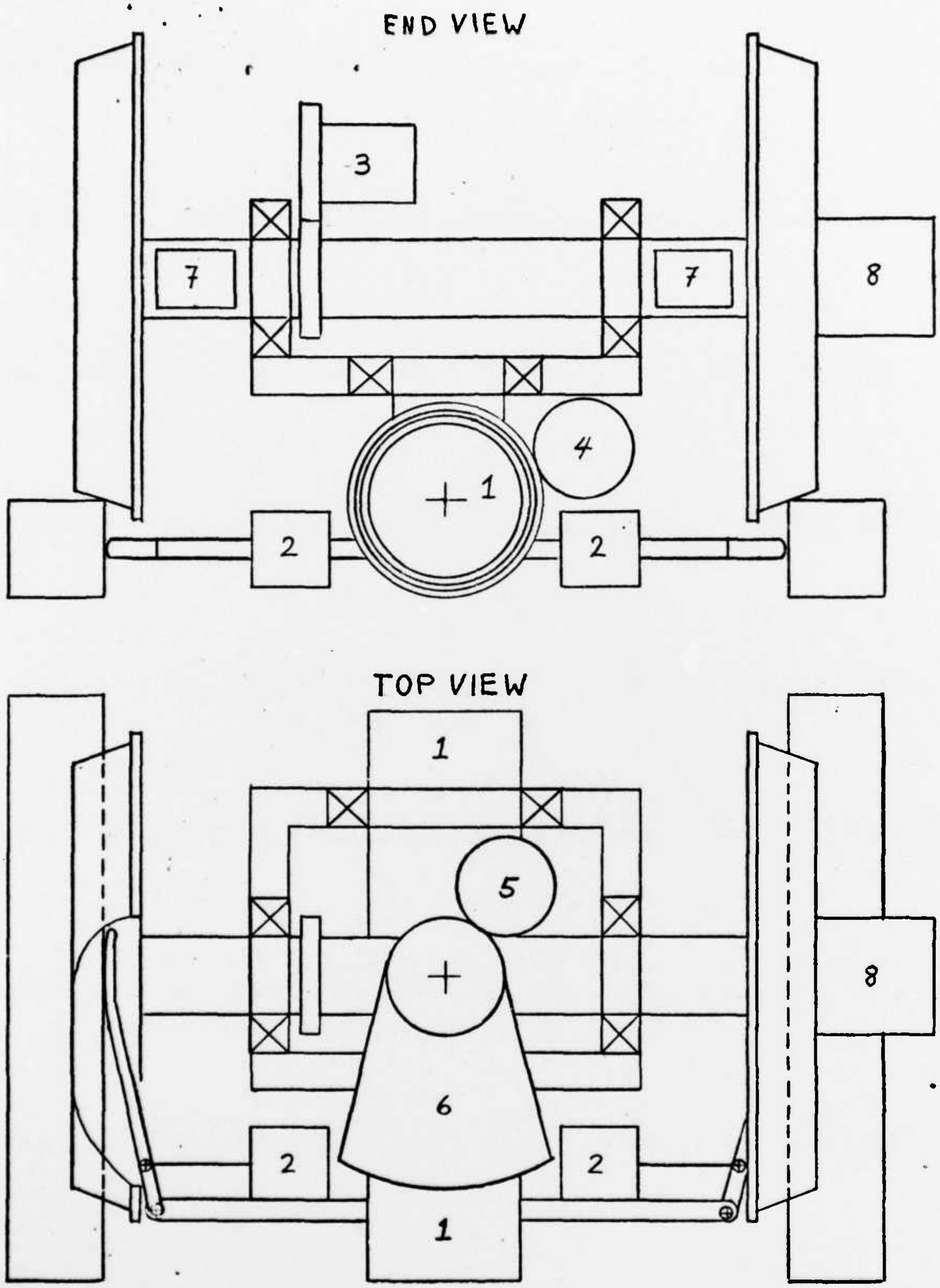
Instrumentation System

Instrumentation associated with the wheelset linkage system has been selected and integrated into the system detailed design. A schematic of the instrumentation system is given in Figure 11.

Lateral position of the wheelset center is measured with displacement transducers that contact the vertical surface of the rail. Roll and yaw angles are measured with precision potentiometers geared to provide necessary sensitivity. These three displacement measurements are sufficient to specify the wheelset position completely; wheelset vertical position is dependent on the three measured quantities through the wheel/rail profile geometry.

A yaw protractor is provided for convenient pre-setting of yaw angle during the fixed yaw angle experiments.

Wheelset body forces are measured with the six-component strain gage balance. As discussed in Quarterly Report I an additional measurement is required to separate longitudinal forces on the two wheels. Torsional strain gages are to be mounted outside the axle bearings to eliminate bearing friction from the measurements. Signals are carried from axle to carriage through precision slip rings.



SINGLE WHEELSET INSTRUMENTATION SCHEMATIC

Figure 11a

NOT TO SCALE
P. WAY 1-24-77

Figure 11b

SINGLE WHEELSET INSTRUMENTATION COMPONENTS

1. GAGE BODY
2. LATERAL TRANSDUCERS -- HEWLETT PACKARD 7DCDT-100
3. TACHOMETER
4. ROLL POTENTIOMETER -- NEW ENGLAND INSTRUMENT COMPANY 5,000 OHMS #7632
5. YAW POTENTIOMETER -- NEW ENGLAND INSTRUMENT COMPANY 5,000 OHMS #7632
6. YAW PROTRACTOR
7. STRAIN GAGES
8. SLIP RINGS -- MICHIGAN SCIENTIFIC COMPANY SR10M

TRACK FABRICATION AND INSTALLATION

During the second quarter the track structure was completed and installed over the full 800 feet of the Princeton Dynamic Model Track. During installation coarse vertical and lateral alignments were performed. As described in Quarterly Report I, the completed track will include steel top plates (currently being installed), aluminum extrusion rail brackets, and the LEXAN rail. Photos of the completed track structure are given in Figure 12.

Samples of LEXAN rail machined to a scaled new rail profile were delivered to Princeton for approval from the rail fabricator. Examination under optical comparators confirmed that the machined profiles met the required specifications. Final machining of the total rail lengths is currently underway.

An improved technique was developed for securing the rails to the aluminum brackets, as shown in Figure 12. The rails are locked in place with fasteners attached to a groove machined in the rail section. The rail is permitted to expand longitudinally, relieving significant buckling, rail gap, and rail fastening problems without track heating; these problems were considered serious ones due to the high coefficient of thermal expansion of LEXAN. This method of rail mounting is functionally similar to that used for real track. In our case, however, the fasteners are used for retention only, with all wheelset forces carried by the aluminum bracket backing the rail.

Figure 12

Rail Safety Research Experimental Apparatus

Photograph	Description
Upper Left	Completed track structure (on left in photo), extending over full 800 feet of Princeton Dynamic Model Track
Upper Right	Installed track structure, showing steel channel sections used for vertical and lateral stiffness, and cross ribs used for torsional rigidity. Threaded studs from channels to floor allow vertical alignment. Section is ready for cold-rolled steel plate and rails to be mounted for track completion.
Lower Left	Section of LEXAN rail mounted to aluminum extrusion bracket. Aluminum bracket takes all rail loadings from wheelset in compression. Rail fasteners locking rail in place shown positioned at two-foot intervals. Rail is retained positively by fastener lips fitted to groove in rail section.
Lower Right	Roller rig used to measure lateral, longitudinal, and spin creep forces on LEXAN wheels and rails, as described in Quarterly Report I.